Sustainable Production and Consumption 30 (2022) 158–170

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Circular use of feed by-products from alcohol production mitigates water scarcity

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ARTICLE INFO

Article history:
Received 18 August 2021
Revised 26 November 2021
Accepted 30 November 2021
Available online 2 December 2021

Editor: Prof. Carmen Teodosiu

Keywords:
Anaerobic digestion
Circular economy
Cooling water
GHG emissions
Spirit
Virtual water

ABSTRACT

The distillery sector is among the biggest industrial water user in the United Kingdom (UK) and simultaneously delivers valuable by-products traditionally used for cattle feed, but in recent years increasingly for bioenergy generation. Our research provides new insight into these two aspects of alcohol production by 1) presenting the first water scarcity footprint of Scottish single malt whisky, and 2) comparing potential avoided water scarcity impacts through the use of by-products to replace different feeds and energy carriers. We applied Life Cycle Assessment, including a water scarcity footprint (AWARE methodology) and carbon footprint, using primary data from a Scottish whisky distillery. By-products used for feed were considered to replace imported soybean meal from the Americas or rapemeal from Europe combined with UK grown barley to balance protein and metabolisable energy substitution. Alternative by-product use for biogas production replaced conventional heat and electricity generation, or transport fuel with the digestate substituting mineral fertilisers. The water scarcity footprint of 1 litre of pure alcohol is 0.79 m^3 world eq., with the majority of water used for cooling, highlighting a hotspot for water conservation. The carbon footprint is 4.4 kg CO_2 eq., predominantly caused by heating with gas oil. By-product use as animal feed, replacing soybean meal and barley, offsets up to 47% of the water scarcity footprint and 32% of the carbon footprint of alcohol production. Using by-products for bioenergy generates smaller offsets. Water reuse and heat recovery measures should be investigated as priorities to reduce the environmental footprint of whisky. Feeding all cereal based by-products from UK potable alcohol production to cattle could save 370 M m^3 world eq., or 37% of the UK's water scarcity footprint attributable to imported soy feed.

Abbreviations

AD	Anaerobic Digestion
AR	Argentina
AWARE	Available Water Remaining
BOD/COC	Biological/chemical oxygen demand
BR	Brazil
CC	Climate Change
CF	Characterisation Factor
CHP	Combined heat and power
DDGS	dried distiller's grains with solubles
DE	Germany
DM	Dry matter
EPD	Environmental Product Declaration
EU	European Union
FR	France
FWC	Freshwater consumption
GHG	Greenhouse gas emissions
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LUC	Land Use Change
LPA	Litre of pure alcohol
NPK	nitrogen, phosphorus, and potassium (mineral fertilisers)
PEF	Product Environmental Footprint
rME	ruminant metabolisable energy

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https://doi.org/10.1016/j.spc.2021.11.034

UK	United Kingdom
US	United States of America
WFN	Water Footprint Network
WSF	Water Scarcity Footprint

1. Introduction

Climate change, an increasing world population, migration, and changing consumption patterns of agricultural products are putting pressure on freshwater resources worldwide (Ercin and Hoekstra, 2014; Schewe et al., 2014; Vörösmarty et al., 2000). Even in the United Kingdom (UK), generally perceived as a water-abundant country, water availability issues are apparent with several water companies' catchments classified as seriously water stressed (EA and NRW, 2013). Water scarcity in the country is expected to increase, with increased risk of extreme drought and a doubling in the frequency of water use restrictions by the year 2050 (Dobson et al., 2020).

Water consumption and scarcity arises via two main routes within industrialised economies: direct or domestic consumption and indirect international consumption via imports of water-intensive commodities, also called external water footprint (Hoekstra and Hung, 2002). Indeed, 62% of the total water footprint of the UK (including rainwater as well as water abstracted from ground and surface water bodies) is made up from water consumed outside the country, of which 73% is linked to agricultural water use (Chapagain and Orr, 2008). Half of the external ground and surface water consumption for products consumed in the UK can be classified as unsustainable (Hoekstra and Mekonnen, 2016). Domestically, the majority of water is withdrawn for industrial, commercial or household use and only 12% is accounted for as agricultural use (FAO, 2016). Water abstraction data from the Environment Agency for England support this trend, reporting 1% of freshwater use for irrigation and 9% for fish farming (EA, 2019).

The spirit industry is one of the most economically important water-intensive sectors in the UK. Across the country, a surge in micro-distilleries led to a 400% increase in the number of distilling enterprises from 90 in 2010 to 475 in 2018 (O'Connor, 2018). Scotch whisky alone contributes approximately 21% to UK and 75% to Scottish food and drink exports by value, adding £5.5 billion in gross value to the UK economy, and distilleries are a popular tourist attraction with 2.2 M visits a year (SWA, 2021a). In Scotland, distilleries abstract 70% of the water licensed for direct abstractions across all industrial and commercial users, of which 80% is used for cooling (SEPA, 2019).

Scientific literature on water use in distilling is very limited, though it is known that commercial spirit production is a water-intensive activity. A study by Amienyo (2012) includes volumetric water demand for the life-cycle of a Scottish grain[1] whisky including packaging as part of a Life Cycle Assessment (LCA). A water footprint study by Köseoğlu (2017) presents an in-depth study on malt whisky according to the guidelines of the Water Footprint Network (Hoekstra et al., 2011), i.e. the water footprint includes green (rainwater), blue (ground and surface water) and grey (water needed to dilute pollutants to acceptable concentration) components. An LCA study on a Swedish single malt whisky contains water consumption in the inventory information but does not consider water footprint as a category in the impact assessment (Eriksson et al., 2016). However, none of these studies accounts for the relative scarcity of water at the abstraction location. Several Life Cycle Impact Assessment (LCIA) methods exist today to evaluate impacts of water consumption, whereas previous methods regarding water impacts focused on degradative issues such as eutrophication, acidification or ecotoxicity. Special progress has been made to address water *scarcity* impacts with the consensus-based development of the AWARE (Available WAter REmaining) methodology (Boulay et al., 2018), which is now the recommended methodology for water scarcity impacts according to the Product Environmental Footprint (PEF) Initiative (Zampori and Pant, 2019), the Life Cycle Initiative of UN Environment (Frischknecht et al., 2016) and the Environmental Product Declaration (EPD) initiative (EPD International AB, 2021), amongst others. In addition to quantifying volumetric freshwater consumption along the life cycle of a product, a water *scarcity* footprint also takes into account the seasonal availability of water in the geographic area where the consumption occurs. To our knowledge, there have been no studies quantifying the water scarcity footprint of any spirit. The first research question addressed in this study is therefore: What is the water scarcity footprint of a Scottish single malt whisky (and which distillery processes contribute most to this footprint)?

The second part of the study is about the use of distillery by-products. Distilleries deliver valuable by-products in the form of spent grain and pot ale, which can be used for a variety of purposes. Traditionally, distillery by-products have been fed to cattle (Crawshaw, 2001). They are rich in protein as spirit production only converts carbohydrates into alcohol. Currently though, only one third of all Scotch whisky by-products are used as animal feed, reflecting a shift from feed to bioenergy production (mostly biogas) between 2012 and 2019, leading to a 57% decline in use for feed (Bell et al., 2019). This is partly a result of incentives offered by the UK and Scottish government for renewable energy technologies (Bell et al., 2019). At the same time, soy comprises approximately 10% of compound animal feed produced in the UK (AHDB, 2020). Imported soybeans contribute 20% to the external cropland footprint of the UK, and together with rape, exhibited the largest absolute increase in external cropland footprint of the UK between 1986 and 2009 (De Ruiter et al., 2016).

A study by Leinonen et al. (2018) showed that the use of by-products can reduce the carbon footprint of a distillery significantly, and hence contribute to the net zero carbon emission goal of the Scotch Whisky Association (SWA, 2021b). Greater GHG emission offset (up to 40%) could be achieved when by-products were used as feed to replace soybean meal and barley, vs. use for biogas based heat and electricity production (up to 27% offset). Avoided land use change, in other words deforestation for soy cultivation, was one of the main drivers of these "credits". Similarly, a study assessing changes in GHG emissions from one of the biggest Irish distilleries when switching by-product use from feed to biogas production showed that 99% of emission savings through biogas were offset by emissions from replacing the currently produced feed through imported feed (O'Shea et al., 2020). This was despite a reduction of 54% of direct GHG emissions of the distillery through biogas replacing a part of the natural gas used. However, to date, no assessment has been made of the water footprint consequences of different by-product use pathways.

The second research question is therefore: To what extent can the water scarcity footprint of whisky production be offset through main uses of distillery by-products?

We applied the LCA methodology based on primary inventory data from the Scottish distillery, Arbikie, for the whisky production part of the study. For completeness and better comparison with other studies, we included inventory based volumetric freshwater consumption and GHG emissions as further environmental categories. Finally, we estimated the maximum avoidable water and carbon footprints using all cereal by-products from UK potable alcohol production

[1] Grain whisky can be based on different grains such as barley, wheat, rye or maize. Malt whisky is made from malted barley only.

2. Materials and methods

2.1. Goal and scope

This study assesses the environmental impacts on water consumption, water scarcity and climate change of the production of Scottish single malt whisky and different scenarios of by-product use. It follows the guidelines for an LCA and encompasses the steps from cradle to gate for the production of the functional unit of 1 litre of pure alcohol (LPA, 100% ethanol) for the production of whisky in an unpackaged form. The system boundaries include barley production, malt production and distillery operations, including all necessary transport, but excluding infrastructure. Maturation is excluded due to lack of data. To assess how different options of by-product use can affect the environmental footprint of whisky production, we applied a system boundary expansion or avoided burden approach as in the ISO 14040 (ISO, 2006) guidelines, previously applied in other LCA studies on the production of spirits (Amienyo, 2012; Eriksson et al., 2016; Leinonen et al., 2018). I.e., the avoided burdens are subtracted from the whisky production footprint.

2.2. Description of the system and inventory

2.2.1. Distillery processes

The inventory of single malt whisky production is based on primary data from Arbikie distillery in Scotland, unless mentioned otherwise, recorded during 2018/19 with a production schedule of eight mashing batches per week. Arbikie uses malt from Scottish grown, non-irrigated barley, as typical for Scotch whisky distilleries (SWA, 2021a). Barley was modelled taking French barley production, adjusted for UK water inputs and outputs, allocating 77% of the impacts to barley grains and the remainder to straw (economic allocation; Blonk Consultants, 2017). The barley is processed to barley malt in a malting house and then delivered to the distillery. Inventory data for malting are average data from three UK malt houses (confidential data). Per batch, about 600 kg malt are mashed in with about 6400 L of water (of which 2500 L is later recycled for the next batch) to solubilise the starch and degrade it to sugars, at a temperature of 64 °C and higher. After mashing, the first by-product, the spent grain, is separated and the remaining liquid – called wort – is cooled down to 18 °C for fermentation. The fermented wort, now called beer wash, is distilled twice at up to 100 °C, and yields an approximately 70% spirit which, after maturation and dilution, becomes whisky. The second by-product, the pot ale, remains after the first distillation. It contains about 5% dry matter (DM) and is rich in protein as it includes the waste yeast. The leftover from the second distillation, spent lees, is predominantly water (Akunna and Walker, 2017) and spread onto land. Components in the spent lees such as biological and chemical oxygen demand (BOD/COD) and copper were modelled according to Akunna and Walker (2017).

Water is supplied from both mains supply (14%) and a borehole (86%). It is treated depending on its use: mash water is treated to ensure potable quality. The process water feeding the cooling tower and steam boiler has to be treated with chemicals to prevent corrosion, scaling, fouling and pathogen growth. Chemical manufacture has been modelled using only the main components due to limited data availability. A minor amount of water is used for cleaning of equipment and facility. Electricity requirement for water treatment and pumping is included in the total electricity use of the distillery which uses UK grid electricity. The steam boiler which heats all processes from mashing to the distillations runs on gas oil (diesel) and loses water due to blow-downs. Fig. 1 shows an overview of the main steps included in the LCA of the production of whisky.

2.2.2. By-product use scenarios

The two most common pathways for distillery by-product use are for livestock feed or bioenergy (Bell et al., 2019). Both were represented in different scenarios. The total dry matter (DM) content of the by-products has been determined using a literature value (311 kg DM/t malt input; Bell et al., 2019) and Arbikie's alcohol yield per malt input (Table 2.1).

2.2.2.1 Feed use scenarios.

Type and origin of replaced feed. We considered soy and rape as being replaced by the by-products. Soy and rape are the two most used oilseeds in the UK to secure sufficient protein supply in animal production, with an average consumption of roughly 1.1 M and 0.7 M tonnes per year during the last decade in the form of cake and meal, respectively (AHDB, 2020).

According to the newest available trade data from 2018, the UK sourced almost 90% of its soybean commodities from South America and the United States (US); some of it indirectly through the Netherlands. Direct data on exports to the UK and an analysis of import and re-export statistics from the Netherlands resulted in the following shares for the three countries of origin, representing 90% of the UK's imports of soy commodities (House, 2020): Argentina (AR): 48%, Brazil (BR): 29%, US: 23%. For the base case, an import mix from these countries was considered, while single countries were considered in a sensitivity analysis.

For the origin of rapemeal, we considered the import from the EU's biggest producers, Germany (DE) and France (FR), as trade statistics didn't allow for a unambiguous conclusion (Eurostat, 2019). France is also the biggest single exporter of rape seeds to the UK (House, 2020). The base case considers the average impact from rape meal production of both countries.

Amount of feed replaced. Due to their considerable protein content, spent grain and pot ale are suitable replacements for protein feed, but they also come with an additional energy content. In order to replace an equal amount of both crude protein and metabolisable energy, the replacement of a combination of the imported protein feeds soy or rapemeal and the domestic energy-feed crop barley is considered. The most common and suitable use is as feed for beef and dairy cattle (Bell et al., 2019), which is why we considered ruminant metabolisable energy (rME) content. As in Lienhardt et al. (2019) and Leinonen et al. (2018), the quantities were determined via linear optimisation, using the Excel solver function, keeping an equal protein and energy content while maximising the amount of feed replaced based on the DM content of the by-product. Where available, the protein and energy content has been taken from primary data, complemented by literature values (Table 1). Characteristics for the replaced feed have been derived from literature (Table 1).

Form of feed. The by-products can either be fed directly in their fresh form (scenario Feed 1) or processed to dried distiller's grains with solubles (DDGS) which conserves them and reduces their weight, allowing for longer storage and transport and thus making their use more flexible (scenario Feed 2) (Stewart, 2014). Water and energy requirements for drying and transport to/from a DDGS facility have been considered. The water content of the by-products when fed fresh is considered to return to the same catchment. For the DDGS case, the water is assumed to evaporate or return to water bodies outside the distillery catchment and therefore counts as consumed.

Overview of the feed use scenarios:

- Feed 1a: direct use of fresh spent grain and pot ale on a nearby farm as cattle feed. Replacing: Imported soybean meal and domestic barley
- Feed 1b: as in 1a, but replacing rapemeal and barley

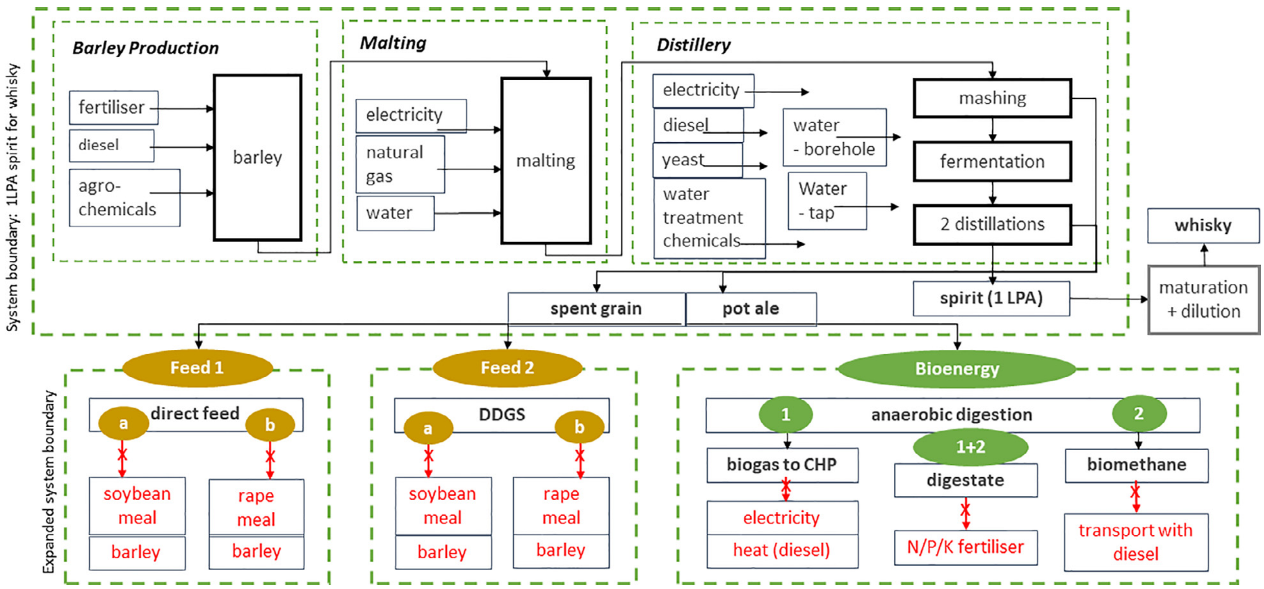

Fig. 1. System boundaries of the Life Cycle Assessment of 1 LPA of spirit for the production of Scottish single malt whisky and expanded boundaries for different scenarios for the use of the by-products spent grain and pot ale.

- Feed 2a: spent grain and pot ale are first processed to DDGS, then used as cattle feed. Replacing: imported soybean meal and domestic barley
- Feed 2b: as in 2a, but replacing rapemeal and barley

2.2.2.2 Bioenergy use scenarios. We considered the two following scenarios for the use of by-products for bioenergy (Fig. 1):

- Bioenergy 1: anaerobic digestion (AD) of by-products to biogas, subsequent combustion in a combined heat and power (CHP) plant. This is currently the most common use for by-products in Scotland (Bell et al., 2019). The digestate from AD replaces mineral NPK fertilisers.
- Bioenergy 2: upgrading of biogas to biomethane for use as transport fuel in a passenger car. Digestate replaces NPK fertilisers.

Biogas production. We assumed the biogas plant is located onsite or very close to the distillery (Clearfleau Group, 2016; O'Shea et al., 2020; Pendrous, 2018). Transport distance for digestate as use for fertiliser considers a conservative distance of 50 km around the biogas plant in accordance with O'Shea et al. (2020). Biogas production includes emissions through methane leakage and considers the amount of parasitic heat and electricity (or its equivalent in biogas for bioenergy scenario 2) which is necessary to run the AD plant. Parasitic amounts are median values taken from a survey of UK biogas plants (Styles et al., 2016), which were statistically indifferent between different plant sizes.

Digestate storage and application. Digestate needs to be stored prior to seasonal application and releases methane (CH_4), ammonia (NH_3) and nitrous oxide (N_2O) during storage. Ammonia emissions vary depending on the type of storage. Here, we consider open tank storage with a moderate NH_3_N emission factor of 10% of NH_4_N, lying in between gas tight tank and open lagoon storage (Styles et al., 2016). Furthermore, emissions of ammonia, nitrous oxide and nitrate (NO_3^-) from field application of the digestate are accounted for, following the method in Styles et al. (2016) based on the MANNER-NPK tool (see next paragraph), resulting in 7.2% of total nitrogen lost as NH_3_N and 9.5% lost as NO_3_N. Nitrous oxide emissions derive from digestate application directly, and indirectly from ammonia and nitrate losses (IPCC, 2006; Styles et al., 2016).

Fertiliser replacement. The MANNER-NPK tool (Nicholson et al., 2013) was employed to determine the amount of mineral fertilisers replaced, assuming digestate application through shallow injection onto a moist sandy clay loam soil and application during March, June and September. This resulted in an average crop availability of 41%, 50% and 89% of the applied nitrogen, phosphorus and potassium, respectively. The available nitrogen amount in the digestate was corrected by losses of NH_3 during digestate storage. Avoided emissions of ammonia, nitrous oxide and nitrate from the avoidance of fertiliser application is considered as in Styles et al. (2016) (seeTable 1 for further details).

Bioenergy scenario 1: The heat generated from the CHP plant replaces the heating fuel (diesel) used in the distillery, while the electricity replaces natural gas as marginal grid electricity (BEIS, 2019). CHP electric and heat efficiency have been considered as for small CHP plants, but different efficiencies are accounted for in the sensitivity analysis. A CHP methane slip of 0.5% is considered according to Styles et al. (2016).

Bioenergy scenario 2: The biogas from AD is upgraded to methane, where carbon dioxide, water, hydrogen sulphide and trace gases are removed. Upgrading comes with an additional energy and material consumption and methane can leak during the process (Adams and McManus, 2019). A fraction of methane is used to run the AD plant, equal to the amount necessary for parasitic electricity and heat requirements in Bioenergy scenario 1. Downstream transport fuel use emissions are considered for a methane fuelled Euro 5 passenger car (Wernet et al., 2016). It replaces diesel driven transport in a Euro 5 passenger car on a vehicle-kilometre basis.

2.3. Life cycle impact assessment

The life cycle impact assessment follows the recommendations of the Product Environmental Footprint (PEF) Initiative by the JRC of the European Commission which is elaborating LCA standards for use with products in the EU (Zampori and Pant, 2019). The recommended LCIA methods comprise the adapted IPCC baseline model of 100 years for Climate Change (CC) impacts and the Available WAter REmaining (AWARE) method (Boulay et al., 2018) for impact on water scarcity (Zampori and Pant, 2019). Additional to the water scarcity footprint (WSF), we calculated the inventory

Table 1
Inventory for whisky production and by-product use in the base case.

Process/material	Quantity	Reference/comment
Barley and malting		
Barley grains per kg malt	1.19 kg	Average of three malting facilities
Allocation of barley cultivation	77% to barley grains 23% to barley straw	Agri-Footprint database for UK barley (Blonk Consultants, 2017)
Water per kg malt	4.5 L	Average of three malting facilities
Thermal energy per kg malt	2.49 MJ	Average of three malting facilities; natural gas
UK grid electricity per kg malt	0.102 kWh	Average of three malting facilities
Distillery		
Barley malt per LPA	2.68 kg	Process data Arbikie
Yeast per LPA	0.0167 kg	Process data Arbikie
Water for mashing per LPA	18.8 L	Process data Arbikie
Water for cleaning per LPA	2.07 L	Process data Arbikie
Water for cooling per LPA	65.7 L	Process data Arbikie; top-up water for cooling tower.
Water for steam boiler per LPA	27.3 L	Process data Arbikie;
Water from borehole vs mains water	86% vs 14%	Process data Arbikie
Thermal energy per LPA	8 kWh	Process data Arbikie; As gas oil
UK grid electricity per LPA	1.17 kWh	(Lienhardt et al., 2019)
Total dry matter in by-products	311 kg/t malt	(Bell et al., 2019)
Spent grain DM	22% (0.593 kg DM/LPA)	anonymous distillery[a]
Spent grain crude protein	24% DM	anonymous distillery[a]
Spent grain rME	10.1 MJ/kg DM	anonymous distillery[a]
Pot ale DM	5% (0.242 kg DM/LPA)	Primary data Arbikie
Pot ale crude protein	37%	(FAO et al., 2020)
Pot ale rME	15 MJ/kg DM	(FAO et al., 2020)
Spent lees	2.94 L/LPA	Primary data Arbikie
Feed scenarios		
DDGS production:		
Thermal energy	5.96 MJ/kg DM	Amount based on (Murphy and Power, 2008); as natural gas (Stewart, 2014)
UK grid electricity	0.129 kWh/kg DM	Based on (Murphy and Power, 2008)
Tap water requirement	2.49 L/kg DM	Based on (Bell, 2000), water evaporated (consumed) only
Avoided feed:		
Soybean meal DM	88%	(FAO et al., 2020)
Soybean meal crude protein	55%	(FAO et al., 2020)
Soybean meal rME	13.4 MJ/kg DM	(FAO et al., 2020)
Rape meal DM	89%	(FAO et al., 2020)
Rape meal crude protein	38%	(FAO et al., 2020)
Rape meal rME	11.1 MJ/kg DM	(FAO et al., 2020)
Barley DM	87%	(FAO et al., 2020)
Barley crude protein	12%	(FAO et al., 2020)
Barley rME	12.4 MJ/kg DM	(FAO et al., 2020)
Bioenergy scenarios		
Anaerobic digestion:		
cumulative methane yield	0.355 m^3/kg DM	(Luna-delRisco et al., 2011)
Digester methane leakage	1%	(Styles et al., 2016)
Parasitic electricity/heat use (Bioenergy scenario 1); parasitic methane use (Bioenergy scenario 2)	6% / 33% (electricity/heat); 22% (methane)	Share of electricity/heat output from CHP needed or share of methane required to run AD. Survey data from UK bioenergy plants (Styles et al., 2016)
Digestate storage:		
CH_4 leakage rate	1.5%	For more complete digestion (Styles et al., 2016)
N content digestate	16%	Of crude protein (FAO et al., 2020)
Digestate total N as NH_4–N	59%	As for brewery waste (Wellinger et al., 2013)
NH_3–N leakage rate (fraction of NH_4–N)	10%	For open tank storage (Styles et al., 2016)
Indirect N_2O–N emission (fraction of NH_3–N emission)	1%	(Styles et al., 2016)
Digestate application:		
NH_3–N emission factor (fraction of NH_4–N)	7.2%	Derived based on (Nicholson et al., 2013)
NO_3–N emission factor (fraction of NH_4–N)	9.5%	Derived based on (Nicholson et al., 2013)
Avoided fertiliser:		
Digestate DM	11%	
Spent grain N content	38.9 g/kg DM	16% of crude protein (FAO et al., 2020)
Pot ale N content	59.8 g/kg DM	16% of crude protein (FAO et al., 2020)
Spent grain P content	3.3 g/kg DM	(FAO et al., 2020)
Pot ale P content	19 g/kg DM	(FAO et al., 2020)
Spent grain K content	0.3 g/kg DM	(FAO et al., 2020)
Pot ale K content	22.3 g/kg DM	(FAO et al., 2020)
Avoided fertiliser application:		
NH_3–N emission factor	1.7%	(Misselbrook et al., 2012)
NO_3–N emission factor	10%	(Duffy et al., 2013)
CHP specifications:		
CHP combustion methane leakage rate	0.5%	(Styles et al., 2016)
CHP electric efficiency	35%	(Styles et al., 2016), for a small plant
CHP thermal efficiency	50%	(Styles et al., 2016), for a small plant
Biomethane scenario:		
Upgrading methane leakage rate	0.5%	(Adams and McManus, 2019)

[a] UK whisky distillery with production scale comparable to Arbikie distillery.

Table 2
Cases for sensitivity analysis on the inventory for whisky by-product use.

case	scenario	description	Base value(s)	Sensitivity value(s)	Reference for sensitivity value(s)
A	all scenarios	higher DM content spent grain, lower DM content pot ale	0.59 / 0.24 kg DM spent grain/pot ale per LPA	0.65 / 0.19 kg DM spent grain/pot ale per LPA	(FAO et al., 2020)
B	all scenarios	lower DM content spent grain, higher DM content pot ale	0.59 / 0.24 kg DM spent grain/pot ale per LPA	0.52 / 0.36 kg DM spent grain/pot ale per LPA	(Pass and Lambert, 2003)
C	Feed scenarios a (soy)	low impact origin only	UK import mix	WSF: BR; CC: US	
D	Feed scenarios a (soy)	high impact origin only	UK import mix	WSF: US; CC: AR	
E	Feed scenarios b (rape)	low impact origin only	DE+FR mix	DE	
F	Feed scenarios b (rape)	high impact origin only	DE+FR mix	FR	
G	Feed scenario 2a+b	lower electricity consumption for DDGS production	0.129 kWh per kg DM	0.096 kWh per kg DM	(Bell et al., 2019)
H	Feed scenario 2a+b	higher heat consumption for DDGS production	5.96 MJ per kg DM	7.27 MJ per kg DM	(Bell et al., 2019)
I	Bioenergy 1 + 2	lower methane yield	0.355 [m^3/kg DM]	−15%	Assumption based on (Luna-delRisco et al., 2011)
J	Bioenergy 1 + 2	higher methane yield	0.355 [m^3/kg DM]	15%	Assumption based on (Luna-delRisco et al., 2011)
K	Bioenergy 1	CHP: lower energy efficiency	35% electric / 50% heat efficiency	30% electric / 40% heat efficiency	(Stewart, 2014) for small plants
L	Bioenergy 1	CHP: different split: electric vs heat energy efficiency	35% electric / 50% heat efficiency	40% electric / 45% heat efficiency	(Styles et al., 2016) for medium and large plants
M	Bioenergy 2	lower biogas upgrading leakage	0.5%	0%	(Adams and Mc-Manus, 2019)
N	Bioenergy 2	higher biogas upgrading leakage	0.5%	2%	(Adams and Mc-Manus, 2019)

based volumetric freshwater consumption (FWC) in order to show the influence of scarcity factors on the results. The LCA has been modelled with the software SimaPro (PRé Sustainability, 2020) using the Ecoinvent database version 3.6 for background information (Wernet et al., 2016).

2.3.1. Water scarcity footprint

The AWARE method defines scarcity based on the available water remaining after human and local ecosystem requirements have been met (Boulay et al., 2018). The method is based on water *consumption*, i.e. only accounts for the water abstracted and used which does not return to the same watershed after use but instead gets incorporated in a product, or – e.g. in case of irrigation – is lost through evapotranspiration by soil and plants. In this study, not all water withdrawn is lost from the watershed, as water from cleaning and spent lees is released on-site and therefore subtracted from the net water scarcity contribution. Similarly, water in directly used spent grain and pot ale (scenario Feed 1) and in digestate (Bioenergy scenarios) is subtracted from net scarcity. The consumed water is the water being incorporated in the spirit and the water for cooling and steam boiler. The cooling water amount considered is the top-up water which is needed to replace the constantly evaporating water in the cooling tower. The volume of top-up water was monitored by Arbikie distillery over the course of a year.

Compared to e.g. GHG emissions which are equal in impact disregarding the point of release, water scarcity impacts are dependant on location of water abstraction. Therefore, characterisation factors (CF) applied to consumed water in the AWARE method represent the water scarcity or available water remaining in a geographic area (watershed) and defined time (month) compared to the world average – expressed in *m^3 world equivalent*. In line with the PEF methodology, we used country and annual aggregated CF which facilitate data acquisition and conform with background data in databases such as Ecoinvent that typically do not specify water inventory flows at watershed level. Even with simplification to country level, proper application of the AWARE method poses challenges because some processes in life cycle inventory databases are not available for the respective country. Special scrutiny has therefore been applied to model the water flows and to assign the geographically-correct scarcity factors by adapting background datasets to the right geography. Table S1 in the Supplementary Information (SI) shows a list of the main processes and their adaptations for regionalisation of water in/outputs.

Crop blue water consumption (irrigation water) relevant for soy and rape cultivation have been taken from the Water Footprint Network (WFN) database (Mekonnen and Hoekstra, 2010).

2.3.2. Climate change

In line with the PEF guidelines which allow for a simplified approach for closed carbon cycles such as those of food products (Zampori and Pant, 2019), uptake and emission of biogenic carbon was not modelled (i.e. CO_2 uptake during plant growth and release during fermentation and use of by-products and spirit). However, other biogenic GHG emissions mentioned above such as methane, as well as ammonia and nitrous oxide emissions from digestate storage and application are included, along with GHG emissions from land use change (LUC) such as through soy cultivation in South America.

2.4. Sensitivity analysis

2.4.1. Sensitivity on the inventory

Sensitivity analysis was applied to variable by-product scenario parameters likely to influence results of water scarcity and GHG emissions – reflecting, e.g., variations in by-product composition (influencing AD methane yield), process scales (CHP efficiency) and applied technology (methane leakage from biogas upgrading). The amount of DM contained in by-products influences all use scenarios, as it is the basis for materials and energy substitution, and has been considered for all scenarios. Regarding the feed scenarios, we split the country import mix of soybean and rape meal into single country origin to show dependence of results on cultivation conditions in the regions. For the water scarcity footprint of soy, we show the difference between its origin from Brazil (lowest impact) and the US (highest impact), while for Climate Change, we show soy from the US (lowest impact) versus Argentina (highest impact).

In each sensitivity case, only one parameter was changed at a time, while others remained constant. A full list of changed parameters and the respective references is given in Table 2.

2.4.2. Sensitivity on the AWARE methodology

Database processes do not provide monthly and watershed level information for water use which would be necessary to link inventory flows to the originally developed AWARE CF. The developers of the AWARE method have therefore provided country and annual average CF which are by default used in the PEF method. However, they don't *recommend* the use of average CF (Boulay et al., 2019). Instead, they propose the use of more refined factors whenever data on a watershed and monthly level are not available. Several improved CF sets have been published: sector specific CF, distinguishing between the agricultural sector's water use ("agri"), and the domestic or industrial sector ("non-agri") (Boulay et al., 2018); regionalised CF for a sub-national level (Boulay and Lenoir, 2020); and for agricultural water use in particular: crop specific CF for 26 crops and 224 countries which take into account crop and location specific water availability and consumption (Boulay et al., 2019). All of these CF sets have been shown to potentially change results significantly and are preferable to the generic country average CF (Boulay et al., 2019; Boulay and Lenoir, 2020; Villanueva-Rey et al., 2018).

In order to test sensitivity of results to the choice of CF, we applied sector and crop-specific CF, where applicable, for all *foreground* or direct water consumption as they are not (yet) compatible with the Ecoinvent database used for background processes. In the first step, sector-specific CF (agri/non-agri) were used with water input and output flows in malting and distilling as well as production of DDGS, soybean and rapemeal, including irrigation water. In a second step, further refinement was achieved by replacing agricultural CF by the crop-specific CF for soy and rape irrigation water.

3. Results

First, the results for both water footprints and for climate change for 1 LPA of whisky are shown, before demonstrating how the whisky production footprint can be reduced through different forms of by-product use. Finally, we present an estimate on the avoidable burdens through by-product use on a national level.

3.1. Environmental burdens from whisky distilling

The FWC of one LPA is 0.13 m^3 and the WSF 0.79 m^3 world eq. Distillery water use dominates both water footprints, with 84% for the water volume consumed and 51% for water scarcity (Fig. 2). In total, about 114 L of water are required in the distillery to produce 1 LPA spirit for whisky split into cooling water (66 L), boiler water (27 L), mashing water (19 L) and the remaining for cleaning (2 L). Barley production causes 6% of the water volume used, but 43% of the water scarcity impacts (Fig. 2) – mainly via water used in global production of fertilisers (especially ammonia and urea). A small amount of water is embedded in electricity generation and the production of water treatment chemicals, yeast and in transport.

The total CC impact for 1 LPA amounts to 4.4 kg CO_2 eq. Distribution of impacts between the life cycle stages and production steps offer a different profile compared with water: 21% from barley cultivation, 14% from malting and 64% from distillery operations (Fig. 2). Emissions from barley cultivation are mainly direct field emissions from fertilisation, as well as emissions from production of fertilisers and use of agricultural machinery. Almost all GHG emissions in malting are due to electricity and heat consumption, which is also the case in the distillery. Heating requirements met through diesel combustion are the single biggest contributor to the overall CC result with 2.3 kg CO_2 eq.

3.2. By-product use

Table S2 in the SI shows the amount of feed, fertilisers, energy and transport avoided in the respective scenarios. Fig. 3 shows the effect that avoided processes and products have on the whisky production footprint per LPA. Water scarcity burdens can be reduced by up to 47% or 0.37 m^3 world eq. when spent grain and pot ale are used as feed without further processing and replacing 0.34 kg of imported soybean meal and 0.42 kg of domestic barley on a DM basis. Similarly, DDGS replacing soy and barley offsets 43% of the water scarcity footprint. The avoided soy footprint is dominated by cultivation in the US, which contributes 80% to water scarcity of the UK import mix despite constituting 23% by mass. With rape replaced instead of soy, 18% and 15% of the WSF can be avoided, when by-products are fed directly or as DDGS, respectively. When by-products are used for bioenergy purposes, 1 kWh electricity and 4.5 MJ fossil heat can be replaced per LPA, avoiding 13% of water scarcity (Bioenergy 1), or 2.4 km of diesel transport can be replaced, reducing water scarcity by 12% (Bioenergy 2).

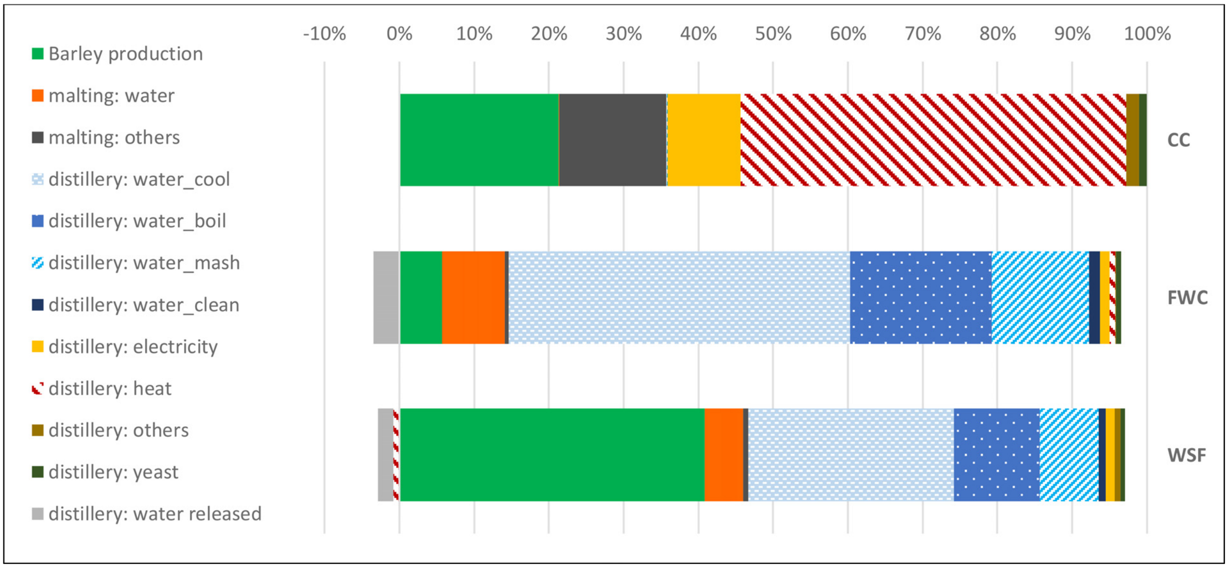

Fig. 2. Results of the LCA of whisky production (1 LPA of spirit) shown as relative contribution of life cycle inputs. WSF = Water Scarcity Footprint; FWC = Freshwater Consumption; CC = Climate Change. Note that water inputs only marginally contribute to CC and therefore don't appear in the graph. Malting: others = transport, electricity and heat; distillery: others = transport and chemicals; distillery: water released = water from cleaning and spent lees.

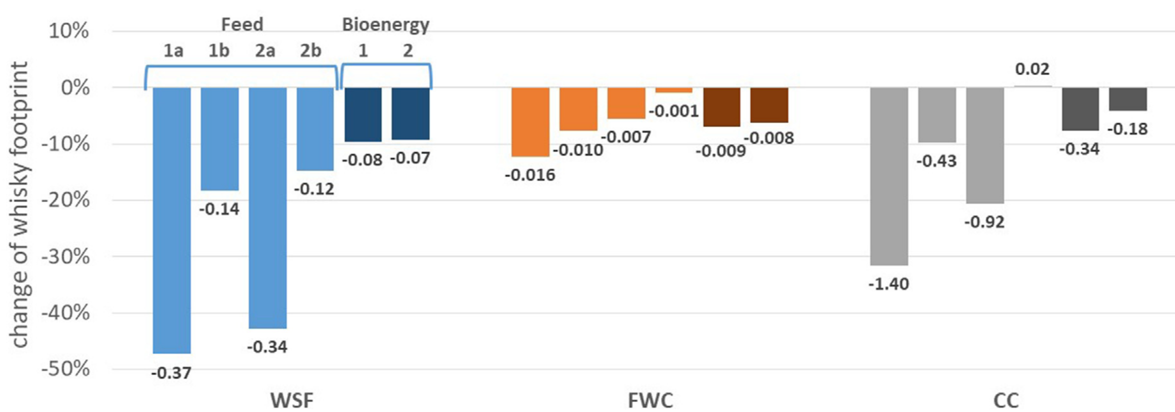

Fig. 3. Change of the whisky production footprint by avoided burdens through by-product use. First four columns of each impact category show changes through feed use scenarios, while last two columns show bioenergy scenarios. Values show avoided footprints ("credits") per functional unit of 1 LPA for whisky production in m^3 world eq. (WSF), m^3 (FWC)) and kg CO_2 eq. (CC).

Freshwater consumption savings are less, ranging from 1 to 12% for the feed scenarios and 6–7% for the bioenergy scenarios. Again, the greatest avoided impact is achievable through replacing soybean meal and barley through feeding the raw by-products.

In the case of climate change, by-product use can offset the whisky production footprint by up to 32% or 1.40 kg CO_2 eq. per LPA, when replacing soy and barley feed. Other than with water scarcity, avoided carbon emissions through soy replacement, are predominantly caused through soybean meal imports from Argentina and its high LUC emissions connected to deforestation. The replacement of rape and barley is only beneficial when by-products are used in their fresh form. In scenario Feed 2b, where spent grain and pot ale are first processed to DDGS, GHG emissions from transport and processing of by-products to DDGS outweigh the avoided emissions from rapemeal and barley production. The use of by-products as a bioenergy resource delivers potential GHG emission savings of 4% to 8%. Emission savings from avoided mineral fertiliser manufacture and application are countered by digestate application emissions of NH_3 and N_2O, which are higher for digestate than for fertiliser application.

3.3. Sensitivity analysis

3.3.1. Sensitivity to inventory change in by-product scenarios

In total, 14 sensitivity cases were examined, of which eight apply to the feed scenarios and seven to the bioenergy scenarios. The highest differences to the base case occurred when changing the origin of the replaced soybean meal. Assuming all soy originated from Brazil, the WSF for whisky would be reduced by 15% (Feed 1a) and 12% (Feed 2a), comparable to reduction potentials through bioenergy. However, if soy from the US was substituted by the by-products, the whisky WSF would be more than offset (Fig. 4). It would result in a final footprint of -0.28 (Feed 1a) and -0.21 m^3 world eq. (Feed 2a) for whisky with by-product use. This is due to the high water scarcity footprint of US soybean meal of 2.56 m^3 world eq./kg, opposed to 0.27 for Argentinian and 0.07 for Brazilian meal. The scarcity footprint is connected to irrigation water requirements which are 92 m^3/t for soy from the US, 5 for Argentina and 1 for Brazil (Mekonnen and Hoekstra, 2010). Furthermore, AWARE CF differ amongst these countries with 33.8 (US), 47.1 (Argentina) and 2.17 (Brazil). Considering that only German

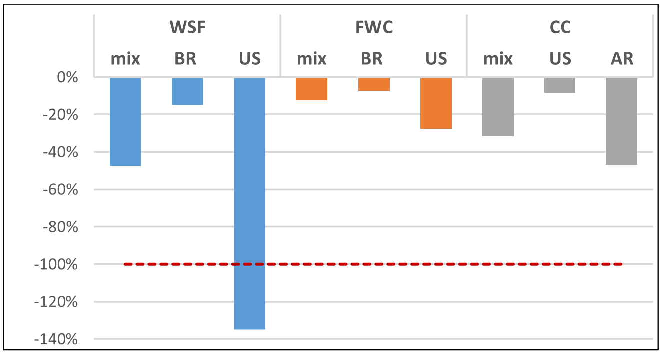

Fig. 4. Sensitivity cases C and D: single country origin of avoided soybean meal. Relative reduction of whisky production footprint shown for scenario Feed 1a: fresh spent grain and pot ale replacing imported soybean meal and UK grown barley. Red dotted line where the whisky footprint is fully offset. BR = Brazil, AR = Argentina. Mix: as in base case, soybean meal from Argentina, Brazil and the US.

rapemeal was replaced, relative reduction of the WSF amounted to 15% (Feed 1b) and 11% (Feed 2b). Freshwater consumption results followed a similar trend as the WSF (Table S3, SI).

The origin of the replaced soy also had a considerable influence on the results in the CC category, however, with a different country trend than for water impacts. CC reduction of the whisky production footprint ranged between 9 and 47%, replacing either soybean meal from the US or Argentina (Feed 1a). Avoided CC emissions are mainly influenced by LUC (deforestation) emissions for soy grown in Argentina and Brazil and which are highest in Argentina, mainly due to conversion of secondary forests into arable land. No LUC emissions were reported for US grown soy (Wernet et al., 2016). In the case of DDGS replacing soybean meal from the US (Feed 2a), the whisky carbon footprint would not be reduced at all. Single country origins for rape meal only changed reduction potentials to a minor extent.

Full sensitivity analysis results are available in the SI, Table S3-S5.

3.3.2. Sensitivity to AWARE CF

Introduction of *sector-specific* CF reduced the WSF of whisky considerably to 0.51 m^3 world eq./LPA, a reduction of 36% (Table S6, SI). This can be explained with the different CF factor which is 3.5 in the base case (UK yearly average, unspecified activity), but 1.3 for UK non-agricultural activities. Changes in avoided footprints through by-product use were comparably small with new avoided scarcity footprints ranging from 0.08 to 0.36 m^3 world eq. compared to previously 0.1 to 0.37 m^3 world eq. However *relative* reduction of the whisky production footprint increased as can be expected, from 16 to 17% for bioenergy scenarios to about 70% for both soy scenarios, as shown in Fig. 5.

Replacing agricultural CF through *crop specific* CF of course did not introduce further changes to the whisky or bioenergy footprint, but only to irrigation water dependant soybean and rapemeal footprints. While reduction potential in the rape scenarios remained almost equal to the sector specific CF case due to low irritation water requirements, reduction potential in the soy scenarios was almost halved and nearer to the base case with 36–38%.

Despite significant changes in net water scarcity footprints with the refined AWARE CF, overall ranking of by-product use options remained very similar. Avoidable footprints through feed by-product use were generally larger than those for bioenergy use, no matter if rape or soybean meal was assumed to be replaced.

4. Discussion

4.1. Distillery footprint: Analysis and comparison to literature

As water abstraction data for the distillery sector have shown, cooling is the hotspot for water use in distilling (SEPA, 2019), and this is no different for Arbikie. The distillery uses an open cooling water loop which includes a cooling tower with fan, i.e. a large fraction of cooling water evaporates. However, this system requires less water than once-through cooling. Investigation into opportunities for lowering the distillery's water footprint should focus on cooling water use. Cooling systems conserving water (but not energy) include chillers relying on the compression of refrigerants or air cooling systems. The latter are restricted to seasonal use due to cooling capacities depending on ambient air temperatures and would require combination with other cooling technologies. Another option with the potential to reduce water *and* energy consumption could be the installation of a closed cooling water loop combined with direct water and heat reuse from cooling for mashing and distillations (Arbikie, personal communication).

Water use figures from literature vary considerably without giving information about the cooling technology used, making it difficult to benchmark Arbikie's water use, although much lower water consumption seems to be achievable(Table 3). In a survey amongst five Scotch whisky distilleries, total direct water consumption per LPA ranged from 55 to 1470 L, with the average being 503 L (assuming the final whisky contains 40% vol alcohol in order to transform the result from litres of whisky to LPA) (Meadows, 2015). Of the three distilleries, where further breakdown was available, cooling water accounted for 89 to 96% of the total water consumption. Other studies reported 7 L/LPA for mashing and 80 L/LPA for cooling in Scotch malt whisky production, though admitting poor data availability (Köseoğlu, 2017) or 56 L/LPA of total direct water consumption for the production of a Swedish single malt whisky (Eriksson et al., 2016). These substantial differences will be caused not only by different cooling water systems but also different production scales.

Several studies could be found which present a carbon footprint of whisky based on an LCA. We only included those life cycle steps in the comparison which best match the system boundaries of this case study (Table 3). Based on the results in Amienyo (2012), a footprint of about 7 kg CO_2/LPA Scotch grain whisky can be derived which includes all steps until (with) bottling but without distribution and packaging (assuming again a content of 40% vol alcohol). Both, the study from Leinonen et al. (2018) on Scotch single malt whisky and the Swedish study (Eriksson et al., 2016) report a footprint of 2.6 kg CO_2/LPA, excluding avoided emissions through by-product use. Leinonen et al. (2018) considered an energy consumption in the distillery of 2.2 kWh/LPA produced, derived from Bell et al. (2012). The Swedish distillery uses solely renewable energy, while natural gas is used in the Scottish one. Distillery operations of the Swedish whisky therefore only account for 0.23 kg of GHG emissions. With 4.4 kg CO_2 eq./LPA, the whisky in this study lies in between the literature values. With an energy consumption of 9.2 kWh/LPA for heating and electricity, Arbikie distillery lies above the average of 8 kWh/LPA based on data from 70 Scottish malt distilleries in 2018 (Sibille, 2020).

In order to mitigate climate change impacts, the greatest opportunity would lie in lowering the consumption of gas oil or changing to a renewable energy source. Changing to an electric boiler has been ruled out as currently not financially viable (Arbikie, personal communication). Trials at Arbikie have shown that energy efficiency could be improved through increased (overnight) production cycles, which reduces gas consumption per LPA produced, as the boiler is not led to cool down during the night when turned off. Another promising measure would be heat recovery

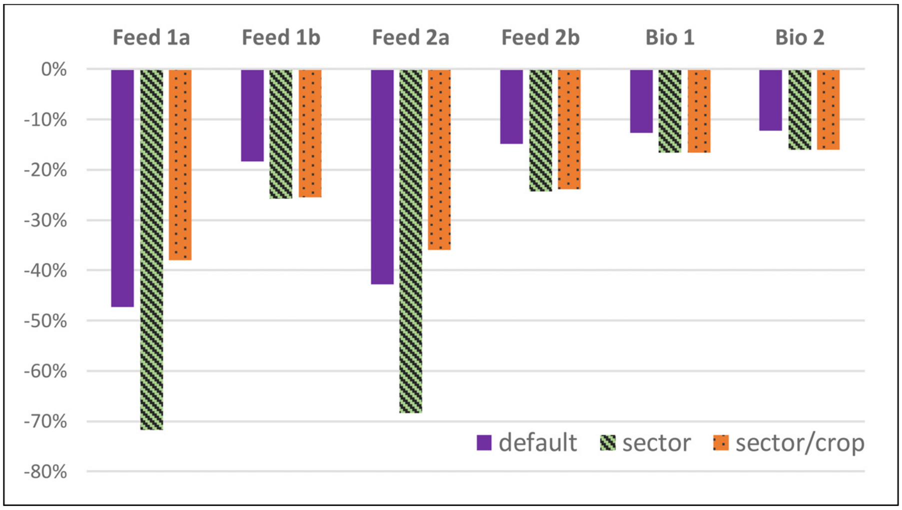

Fig. 5. Sensitivity analysis with different AWARE characterisation factors (CF) in the foreground processes. Bio=Bioenergy scenario. Default: use of annual and country average CF. Sector: use of sector specific (agri/non-agri) CF. Sector/crop: use of sector specific CF apart from irrigation water where crop specific CF are applied.

Table 3
Comparison of water use and energy inventory data and GHG emissions for whisky production reported in the literature vs this study.

	Scope	This study	Literature	Reference
Water use [L/LPA]	Distillery operations	114	55–1470[a]	(Meadows, 2015)
			56[b]	(Eriksson et al., 2016)
	Cooling only	66	238–1418[a]	(Meadows, 2015)
			80	(Köseoğlu, 2017)
	Mashing only	19	7	(Köseoğlu, 2017)
GHG emissions [CO_2 eq./LPA]	Life cycle, incl. distillery operations	4.4	7[a,c]	(Amienyo, 2012)
			2.6	(Leinonen et al., 2018)
			2.6[b]	(Eriksson et al., 2016)
	Distillery operations only	2.8	0.23[b]	(Eriksson et al., 2016)
Energy use [kWh/LPA]	Distillery operations only	9.2	2.2	(Leinonen et al., 2018; Bell, Morgan, Dick and Reid, 2012)
			8[d]	(Sibille, 2020)

[a] assuming 40% vol alcohol content.
[b] considering 43.5% vol alcohol content according to the authors.
[c] includes bottling.
[d] average of 70 Scottish malt distilleries.

from mashing and distillation, as well as from by-product streams. This is currently being investigated at the distillery. Energy integration, linking heat sources and sinks across several plants could pose a promising option to reduce energy consumption for distilleries located in a cluster with other distilleries, biogas or DDGS plants. Water savings would also contribute to reduction of indirect GHG emissions connected to water treatment (e.g. chemicals, pumping), both at a utility in the case of mains water, as well as at the distillery (Rothausen and Conway, 2011; Walker et al., 2021).

4.2. By-product use – analysis and national potential

Our study comes to a similar conclusion as Leinonen et al. (2018), who looked at GHG emissions only, on the largest environmental credits being achieved from livestock feed use of distillery by-products. However, this study introduces novel evidence on the contribution of by-product use to water scarcity offsetting in whisky production. Both from a water scarcity and from a climate change perspective, feed use of by-products is the preferable option if it contributes to domestic feed supply and decreases the import of soybean meal to the UK. Crucially, we showed that water scarcity offsets can in some cases be greater than the alcohol footprint, and that "hotspot" animal feed export countries are different for water scarcity (US soy) than for GHG emissions (Argentinian soy).

The greatest water scarcity footprint offsets can be achieved when distillery by-products are used as animal feed to substitute imported soybean meal as well as rapemeal, with only a few exceptions in the sensitivity cases where crop country origin led to similar results as in the bioenergy scenarios. Reductions in climate change impacts are more sensitive to the origin of replaced feed commodities and to energy-intensive processing of by-products into DDGS, but also reach highest reduction potentials replacing soybean meal.

During the last ten years, on average, roughly 1100 kt (kilo tonnes) of animal feed production in the UK was based on soy cake and meal (AHDB, 2020). By-products from cereal-based alcohol production in the UK can be quantified at 826 kt DM annually, using data on barley and wheat use by UK brewers, maltsters and distillers for potable alcohol production (AHDB, 2021), and fresh weight to by-product conversion factors from Bell et al. (2019).

If all cereal alcohol by-products were used to substitute imported soybean feed combined with domestic barley, the consumption of 16 M m^3 of freshwater could be avoided – assuming that barley and wheat based by-products replace the same amount of feed. This equals 39% of the total direct water use of all Scottish distilleries (data from 2015 to 2017; SEPA, 2019).

The avoided water *scarcity* footprint would amount to a total of 370 M m^3 world eq., of which 300 M is attributable to soy replacement, and would reduce the UK's external water scarcity footprint, and 70 M is attributable to barley replacement. Savings through soy replacement equal 37% of the water scarcity footprint from imported soy cake and meal used for feed.

The potential carbon savings would comprise 1.3 M t CO_2 eq., with all extrapolations applying the methodological choices of the base case of this study. The use of by-products for feed purposes can be regarded as a measure to lower the UK's dependence on foreign water resources and to lower the UK's external water footprint and water risk (Ercin et al., 2019; Hoekstra and Mekonnen, 2016; Qu et al., 2018). From a carbon and water perspective, feed use can be suitable to avoid "external" emissions made through UK imports in the feed and food supply chain. Whisky by-products therefore deserve recognition as a domestic, high quality and low budget resource for feed.

4.3. Limitations of the study and recommendations for future research

While data quality was very high for water use in malting and distilling owing to availability of monitored primary data, our study relied mostly on literature data for the by-product scenarios where inventory choices had to be made. The sensitivity analysis showed that WSF results for feed scenarios including soy were sensitive to country of origin and with it irrigation water requirements. The latter are influenced by the calculation method of crop water requirements and choice of respective database, of which various exist which differ in resulting crop water requirement from the WFN database used here (Hoekstra and Mekonnen, 2010; Kounina et al., 2013; Payen et al., 2018a). For instance, crop blue water consumption data from Pfister and Bayer (2014) were not taken, as they calculate a considerable irrigation water consumption for UK barley, which is not the case for Arbikie's barley (Arbikie, personal communication) and extremely rare for UK cereals in general (Chatterton et al., 2010; Watts et al., 2015). However, as we used consistent data sources for irrigation water requirements across incurred and avoided processes, our results should be relatively robust to some of these uncertainties. Further work is needed to explore water footprint results from different databases.

The sensitivity analysis for the AWARE CF showed that application of more accurate CF can change results to a large extent, supporting previous findings (Payen et al., 2018b; Villanueva-Rey et al., 2018). However, the application of the AWARE method is still in its infancy with the consequence that databases and software do not yet contain water inventory flows which go beyond country resolution to be specific for a sector, region or watershed. It is expected that adaptations to inventory datasets will be implemented in the future.

Looking beyond the AWARE method, there exist different life cycle impact assessment methods for water scarcity footprints being discussed in the LCA community. It has been shown for different products that choice of methodology does influence water *scarcity* results and in some cases can change product rankings (Caldeira et al., 2018; Jeswani and Azapagic, 2011; Payen et al., 2018b; Villanueva-Rey et al., 2018). However, the AWARE method chosen here, can currently be regarded as the "most up to date and precise" (Villanueva-Rey et al., 2018) one for blue water consumption impacts (Boulay et al., 2018). A methodological comparison could be the focus of a future study.

5. Conclusion

This study presents the first water scarcity footprint for a Scottish single malt whisky based on primary data from a distillery. By-product use was included in the study to understand its potential impacts on the whisky production footprint under different use scenarios. Application of the AWARE method for water scarcity with standard average CF generated a footprint of 0.79 m^3 world eq./LPA in the base case, which was reduced to 0.51 m^3 world eq./LPA when more refined CF were used. The footprint was dominated by distillery water consumption, which was mainly determined through cooling water demand. Measures to reduce the water footprint of whisky production should therefore focus on cooling processes. The climate change footprint was 4.4 kg CO_2 eq./LPA, with heating having the greatest impact.

In the base case, the spirit WSF could be reduced by up to 47% when by-products are used as feed replacing imported soybean meal and domestic barley. This was mainly due to (avoided) irrigation requirements for soy in the producing countries Brazil, Argentina and the US. When used for bioenergy, the WSF could be reduced by 12–13%. For CC, the largest offset could again be achieved through replacement of soybean meal feed, although reduction potentials were more sensitive to modelling choices. Whilst the largest WSF credits were generated from substitution of US soy (avoided irrigation), the largest CC credits were generated through substitution of Argentinian soy (avoided agricultural land transformation).

This study has provided new insight into the role that distillery by-products could play in reducing the UK's external water footprint whilst contributing to national feed (and thus food) security. If all cereal by-products from UK potable alcohol production were used for feed purposes to replace imported soybean meal and home-grown barley, it was estimated that a water scarcity footprint of 370 m^3 world eq. could be avoided annually. Recent government policies have incentivised the use of whisky (and other) by-products for use as bioenergy (biogas) feedstock instead of feed. New water footprint results presented here add to the evidence that policies intended to derive value from "waste" feedstock need to carefully consider the range of feasible alternative uses in order to effectively address *global* sustainability challenges; avoiding unintentional displacement of environmental impacts overseas.

Funding

This research is part of the Dŵr Uisce project, which aims at improving the long-term sustainability of water supply, treatment and end-use in Ireland and Wales. The project has been supported by the European Regional Development Fund (ERDF) Interreg Ireland-Wales Programme 2014–2023 (grant number 14122).

Declaration of competing interest

The authors have no financial or non-financial interests to disclose.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.11.034.

CRediT authorship contribution statement

Isabel Schestak: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **David Styles:** Conceptualization, Writing – review & editing, Supervision. **Kirsty Black:** Investigation, Writing – review & editing. **A. Prysor Williams:** Writing – review & editing, Supervision, Project administration.

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